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Cold gas in the center of radio-loud galaxies

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CHAPTER 5

THE WARM MOLECULAR HYDROGEN OF PKS B1718–649. FEEDING A NEWLY BORN RADIO AGN

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Abstract

We present new SINFONI VLT observations of molecular hydrogen (H_2) in the central regions (< 2.5 kpc) of the closest young radio source PKS B1718–649. We study the distribution of the H_2 traced by the 1-0 S(1) ro-vibrational line, revealing a double disk structure with the kinematics of both disks characterised by rotation. An outer disk ($r > 650$ pc) is aligned with other components of the galaxy (atomic hydrogen, stars, dust), while the inner disk ($r < 600$ pc) is perpendicular to it and is polar with respect to the stellar distribution. However, in the innermost 75 pc, the data show the presence of H_2 gas red-shifted with respect to the rotating inner disk ($\Delta v \sim +150 \text{ km s}^{-1}$), which may trace gas falling into the super massive black hole associated with the central radio source. Along the same line of sight, earlier observations had shown the presence in the central regions of PKS B1718–649 of clouds of atomic hydrogen with similar unsettled kinematics. The range of velocities and mass of these unsettled clouds of H I and H_2 suggest they may be actively contributing to fuelling the central newly born radio source.

5.1 Introduction

Active galactic nuclei (AGN) are associated with the accretion of material onto the central super-massive black hole (SMBH) of galaxies. The gas surrounding the SMBH must lose angular momentum in order to fall into it so it can trigger and feed an active nucleus. Nevertheless, direct observational evidence of this process is still limited. Statistically, galaxies that have undergone a merger or an interaction event have a higher probability of hosting an AGN (Ellison et al., 2008; Ramos Almeida et al., 2012; Hwang et al., 2012; Sabater et al., 2013). However, in several objects with signatures of past mergers or accretion, the timescales associated with these phenomena can be much longer than the age of the AGN (e.g. Emonts et al. 2006; Tadhunter 2008; Schawinski et al. 2010; Struve & Conway 2012 and Chapter 4), suggesting that the link between mergers/accretion and AGN in these galaxies is, at most, indirect, and other processes must occur to trigger the nuclear activity. Slow secular processes may help the gas lose angular momentum on short timescales ($\sim 10^5 - 10^8$ years) and form a dense gas core in the central 100 pc (Kormendy & Kennicutt, 2004; Wada, 2003; Combes, 2004, 2010). However, it is not clear whether these phenomena are efficient in the very innermost regions near the AGN (Athanasoula et al., 2005; Begelman & Shlosman, 2009). Thus, other processes taking place on small spatial and temporal scales are expected to be responsible for the direct fuelling onto the AGN (Wada & Tomisaka, 2004; King & Pringle, 2007; Hopkins & Quataert, 2010). Numerical simulations suggest that gravitational and thermal instabilities induce chaotic collisions in the interstellar medium ISM surrounding the SMBH (Soker, 2009; Gaspari et al., 2013; King et al., 2008; Nayakshin & Zubovas, 2012; King & Nixon, 2015). This causes small clouds or filaments of gas to lose angular momentum and begin a series of small-scale, randomly oriented accretion events, which then trigger the AGN. In this scenario, the gas deviating from regular rotation is responsible for the chaotic infall of clouds and, consequently, for the accretion onto of the AGN (Gaspari, 2015; Gaspari et al., 2016).

High spatial resolution observations tracing in particular the cold gas in the innermost regions of AGN are needed to investigate these hypotheses. Different types of AGN, such as Seyfert galaxies (Gallimore et al., 1999; Mundell et al., 2003; Hicks et al., 2009, 2013; Combes et al., 2014; Mezcuca et al., 2015), low-ionisation nuclear emission region galaxies (LINER; García-Burillo et al., 2005; Müller-Sánchez et al., 2013), and radio galaxies (Neumayer et al., 2007; Dasyra & Combes, 2011; Morganti et al., 2013a,b; Guillard et al., 2015), are rich in molecular (H_2) and atomic hydrogen (H I), which may represent the fuel reservoir for the nuclear activity. Indeed, the kinematics of at least part of this gas often appears to be unsettled with respect to the regular rotation of the galaxy, suggesting a strong interplay between the nuclear activity and the surrounding environment. On the one hand, it is likely that plasma ejected by the radio source perturbs the neutral and molecular hydrogen (Neumayer et al., 2007; Hicks et al., 2009; Dasyra & Combes, 2011; Guillard et al., 2015; Müller-Sánchez et al., 2013; Mezcuca et al., 2015). On the other hand, it is also possible that this reflects the presence of processes such as those described above that can cause the gas to stream towards the SMBH and trigger the nuclear activity (Hopkins & Quataert, 2010; Combes et al., 2014).

Young radio sources in the first stages of their activity (Murgia, 2003; Fanti, 2009) are the best candidates for studying the relation between the kinematics of the cold gas and the triggering of the AGN. They are often embedded in a dense gaseous environment where the fuelling of the AGN has just begun and is likely to be continuing. Also, amongst all radio AGN, these sources show neutral and molecular gas with unsettled

kinematics in proximity of the core relatively often (e.g. Emonts et al. 2010; Geréb et al. 2015b; Curran et al. 2013a; Guillard et al. 2015; Allison et al. 2015 and Chapter 1).

PKS B1718–649 is a compact radio source ($r_{\text{radio}} \lesssim 2$ pc) with an optically classified LINER AGN (Filippenko, 1985) at a distance¹ of ~ 62 Mpc. The estimated age of the radio activity is $\sim 10^2$ years (Tingay et al., 1997; Giroletti & Polatidis, 2009). PKS B1718–649 is morphologically classified as an S0-SABb early-type galaxy embedded in a disk of neutral hydrogen (see Fig. 5.1), which shows regular rotation out to large radii (~ 23 kpc). Given the long timescale for such a regular disk to form, this excludes a merger or a disruptive event being directly responsible for the recent triggering of the central radio source. The accretion onto the SMBH and the fuelling of the radio activity could find their origin in a small-scale phenomenon. The detection, in H I absorption, of two separate clouds with kinematics deviating from the rotation of the disk suggests that a population of clouds may be contributing to feeding the AGN in the centre (Chapter 4). The regions close to the radio source have been indirectly probed by the study of the variability of the radio continuum emission (Tingay et al., 2015), which has been attributed to changes in the free-free absorption due to a clumpy circum-nuclear medium around the radio source. The presence of such a clumpy medium has also been suggested by optical spectroscopic observations (Filippenko, 1985). The available information on PKS B1718–649 suggests that the origin of its newly born radio activity may be found in the kinematics of its circum-nuclear medium.

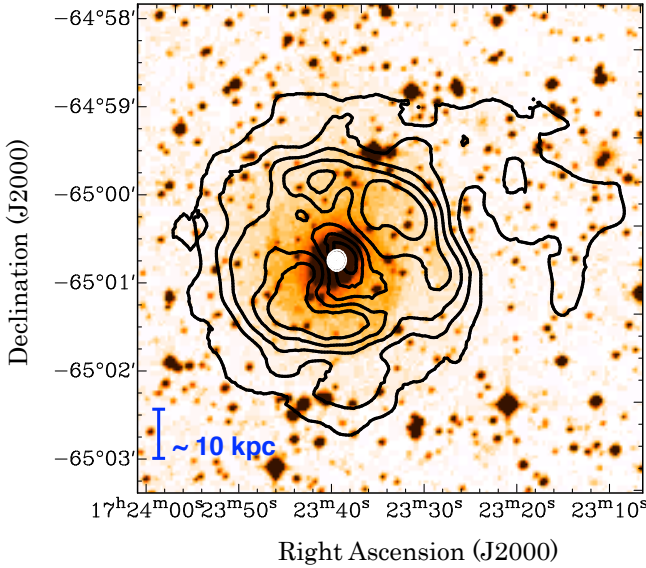


Fig. 5.1: *I*-band optical image of PKS B1718–649, overlaid with the column density contours (black) of the neutral gas. The contour levels range between $7 \times 10^{19} \text{ cm}^{-2}$ and $8 \times 10^{20} \text{ cm}^{-2}$ in steps of $1.5 \times 10^{20} \text{ cm}^{-2}$. The unresolved continuum radio source is indicated in white. The H I disk has the shape of an incomplete ring with asymmetries in the NW and in the S of the disk Chapter 4.

¹ $z = 0.014428$; $D_L = 62.4$ Mpc, 1 arcsec = 0.294 kpc; where Λ CDM cosmology is assumed, $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_\Lambda = 0.7$, $\Omega_M = 0.3$.

Table 5.1: SINFONI observation specifications

Parameter	Value
Field of view	$8'' \times 8''$ (2.37×2.37 kpc)
Pixel size	$0.125''$ (37 pc)
Spectral resolution (at $2.1 \mu\text{m}$)	75 km s^{-1} ($R=4000$)
Spectral sampling (at $2.5 \mu\text{m}$)	36 km s^{-1}
Seeing (run 1, run 2, run 3)	$0.4''$ (131 pc); $2.49''$ (735 pc); $0.52''$ (154 pc)

Integral field unit (IFU) instruments allow us to analyse the spatial distribution and kinematics of the ISM in the innermost regions of low-redshift AGN. Here we present the results obtained for PKS B1718–649 using the Spectrograph for INtegral Field Observations in the Near Infrared (SINFONI) on the VLT. The detection of the molecular hydrogen traced by its ro-vibrational states ($T_{\text{ex}} \sim 10^3 \text{ K}$, H_2 1-0 S(0,1,2,3)) allows us to study its distribution and kinematics and to provide interesting insight into the role of the H_2 in relation to the fuelling of the central radio source.

5.2 Observations and data reduction

We observed the inner 2.5 kpc region of PKS B1718–649 in the K band ($1.95 - 2.45 \mu\text{m}$), using SINFONI (Eisenhauer et al., 2003) mounted on the Very Large Telescope (VLT) UT4. The observations were performed under seeing-limited conditions during three different nights (May 18-26-29, 2014) in period 93A. The spectral resolution is $R \sim 4000$, and the plate scale is $0.125'' \times 0.250'' \text{ pixel}^{-1}$, yielding a field of view of $8'' \times 8''$. The full width half maximum (FWHM) of the sky lines is $6.5 \pm 0.5 \text{ \AA}$, with a spectral sampling of $2.45 \text{ \AA pixel}^{-1}$. Bad seeing conditions caused us to exclude the May 26 observations.

We reduced the data using the official ESO REFLEX workflow for the SINFONI pipeline (version 2.6.8) and the standard calibration frames provided by ESO. The workflow allowed us to derive and apply the corrections for dark subtraction, flat fielding, detector linearity, geometrical distortion, and wavelength calibration to each object and sky frame. Following Davies (2007), we subtracted the sky from the data cubes of the two observing blocks. The typical error on the wavelength calibration is 1.5 \AA (15 km s^{-1}).

Through IDL routines implemented by Piqueras López (2014), we calibrated the flux of each cube. First, we obtained the atmospheric transmission curve, extracting the spectra of the standard stars with an aperture of 5σ of the best 2D Gaussian fit of a collapsed cube. Then we normalised these spectra using a black-body profile at the temperature T_e that corresponds to the spectral type of the observed stars (as tabulated in the 2MASS catalogue, see Skrutskie et al. (2006)), using Table 5 in Pecaut & Mamajek (2013). We modelled the stellar hydrogen Br γ absorption line at $2.166 \mu\text{m}$ with a Lorentzian profile to determine the sensitivity function for the atmospheric transmission (Bedregal et al., 2009). We converted the star spectra from counts to physical units with a conversion factor extracted using the tabulated K magnitudes in the 2MASS catalogue.

We obtained the full-calibrated data cube by dividing each spectrum by the sensitivity function and multiplying it by the conversion factor. The typical uncertainty for the flux calibration is 10%. We combined the two cubes of the single observing runs into the final one by spatially matching the peaks in the emission of the galaxy. The spatial resolution

of the final data cube is equal to the *FWHM* of a 2D Gaussian we fit to the central region of the collapsed cube: 0.52 arcseconds.

In the final cube, we determined whether a line of the ro-vibrational states of the H_2 is detected by considering the spectra extracted over regions of size equal to the spatial resolution of the observations. In Fig. 5.3 we show the spectra extracted in five different regions of the H_2 distribution, approximately in the north (R_N), the south (R_S), the west (R_W), the east (R_E), and in the centre (R_C) (see Fig. 5.2). In all five regions, we detect the H_2 1-0 S(1) line, the brightest in the spectrum, at $2.14\mu\text{m}$, as well as the H_2 1-0 S(3) line, while we do not detect the H_2 1-0 S(0,2), and the higher excited states of molecular hydrogen, H_2 2-1 S(1,3). In this case, we determine the 3σ upper limits assuming a *FWHM* of the line equal to the one of the H_2 1-0 S(1) line. $\text{Br}\gamma$ and [Si VI], tracers of high-excitation ionized gas, are also expected in the same spectral range, but lie below the detection limit of these observations. In Table 5.2, we list the flux densities and upper limits of the lines for the five different regions.

Table 5.2: Line flux density of the molecular hydrogen gas in five regions of the SINFONI field of view.

Line [λ_{rest}]	R_N	R_S	R_W	R_E	R_C
H_2 1-0 S(3) [1.95 μm]	20.2 \pm 1.29	6.88 \pm 1.17	11.4 \pm 1.52	14.1 \pm 1.62	8.35 \pm 3.08
[Si VI] [1.96 μm]	<3.88	<3.52	<4.55	<4.86	<8.88
H_2 1-0 S(2) [2.03 μm]	<5.85	<6.59	<5.51	<7.33	<10.3
H_2 2-1 S(3) [2.07 μm]	<6.41	<3.64	<4.89	<5.90	<8.04
H_2 1-0 S(1) [2.12 μm]	24.2 \pm 0.737	11.6 \pm 1.62	19.1 \pm 0.659	16.1 \pm 0.835	44.6 \pm 6.15
$\text{Br}\gamma$ [2.16 μm]	<4.01	<4.01	<4.56	<6.19	<4.55
H_2 1-0 S(0) [2.22 μm]	<6.39	<3.61	<5.63	<7.54	<10.2
H_2 2-1 S(1) [2.24 μm]	<4.73	<6.81	<4.59	<9.09	<10.4

Notes. The flux densities are given in units of $\times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2}$. The upper limits indicate the $3\text{-}\sigma$ noise level, measured in the wavelength ranges where we expect to detect the lines. The spectra are extracted in five regions, R_N , R_S , R_W , R_E , R_C of the field of view shown in Fig. 5.2. Their sizes correspond to the spatial resolution of the observations (0.52'').

We have focused on the H_2 1-0 S(1) line to determine the distribution and the kinematics of the molecular hydrogen and used the integrated flux densities or the upper limits of the H_2 1-0 S(0,1,2,3) lines to determine the temperature of the molecular hydrogen and its mass. We derived the distribution and kinematics of the H_2 1-0 S(1) emission line using two independent methods, which provide consistent results. In the first method, we spatially smooth the cube with a Gaussian with *FWHM* $\sim 0.5''$ and fit a single Gaussian component to the H_2 1-0 S(1) line in each pixel of the field of view. We build a mask of the regions of pure line emission, selecting the pixels where the H_2 1-0

S(1) line is detected with signal-to-noise ratio of $S/N > 5$. We extend the mask to also consider regions neighbouring the ones where the fit is successful. Following this, for each pixel within the mask, we extract the spectrum and we fit the H_2 1–0 S(1,3) lines with a single Gaussian component. We derive the intensity and velocity fields of the H_2 1–0 S(1) line only in the regions where the two lines are detected.

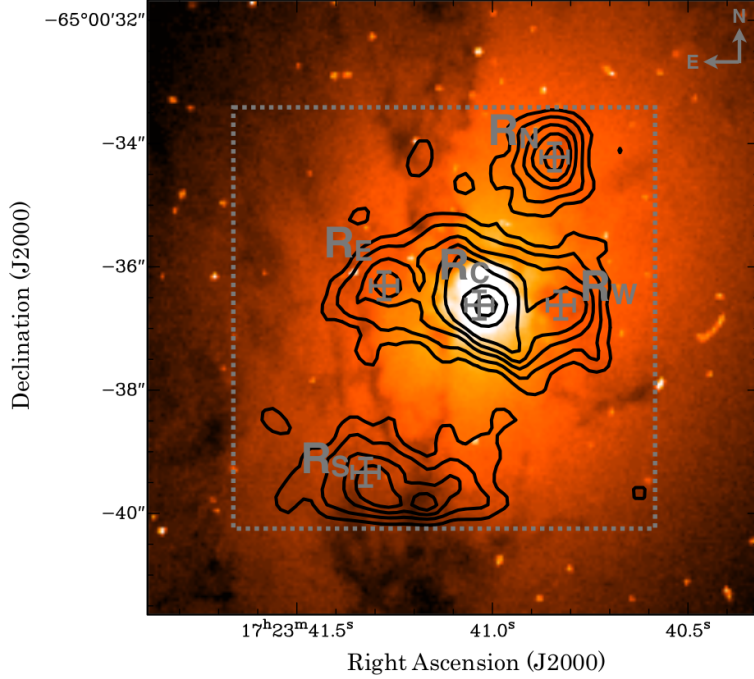


Fig. 5.2: Distribution of molecular hydrogen (black contours) overlaid onto the *Hubble Space Telescope* WFC2 image. A dust lane is visible, oriented in the north-south direction. The grey crosses mark the regions where we extracted the spectra to measure the temperature of the H_2 . The grey dashed square indicates the SINFONI field of view.

In the second method, we build a cube free of emission-line signal by masking out the regions where the H_2 1–0 S(1) line is detected above the $2.5\text{-}\sigma$ level channel-by-channel. Next, we smooth the edges of the masked regions to completely exclude any residual emission-line signal. From this cube, we determine the template of the stellar continuum spectrum. We subtract this stellar spectrum from every pixel where the H_2 1–0 S(1) line is detected and obtain a data cube of pure emission-line spectra. We determine the distribution of the H_2 as the zeroth moment map of this cube, summing all emission above the $3\text{-}\sigma$ level along the velocity axis in at least two consecutive pixels. The velocity field corresponds to the first moment map and is centred on the systemic velocity of the H I disk, $v_{\text{sys}} = 4274 \text{ km s}^{-1}$ Chapter 4.

This method is less conservative than the first, but does not rely on the quality of the Gaussian fitting, which may bias the characterisation of the morphology of the H_2 1–0 S(1) emission. Interestingly, the total intensity and velocity field determined from the two methods are very similar. In the next section, we use the results of the second method to analyse the kinematics of the molecular hydrogen in PKS B1718–649.

The Gaussian fitting of the H_2 1-0 S(1) line describes the line across the field of view well, except in the central $0.52''$ in the proximity of the AGN. This is the only region where the fit with a single Gaussian component leaves substantial residuals above 3σ of the noise (see Fig. 5.3 right panels). The profile is also clearly more asymmetric, and the velocity dispersion of the profile is higher than in the other regions of the field of view. This suggests that in the centre, more than one component is needed to fully characterise the kinematics of the H_2 . A further analysis of the morphology of the H_2 1-0 S(1) emission in the central 75 pc of PKS B1718–649 is given in Section 5.3.2.

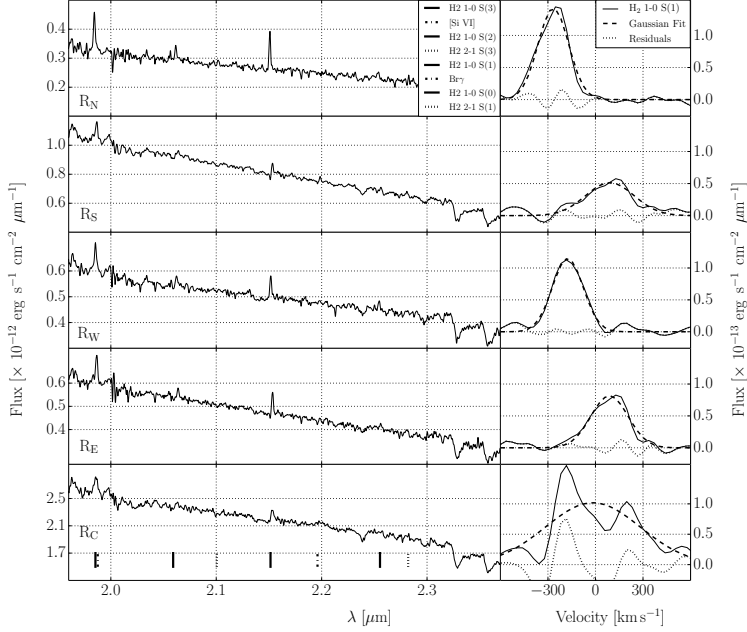


Fig. 5.3: Spectra extracted from the five regions (R_N , R_S , R_W , R_E , R_C) illustrated in Fig. 5.2. The right panels show a zoom-in on the H_2 1-0 S(1) line, centred at the systemic velocity of PKS B1718–649. The dashed line shows the fit with a single Gaussian component, while the dotted line shows the residuals. In the bottom panel, solid lines indicate the locations of the H_2 1-0 S(0,1,2,3) lines, while dashed and dotted lines show the H_2 2-1 S(1,3) and [Si VI] and Br γ lines, respectively.

5.3 Results

5.3.1 Distribution and kinematics of the molecular hydrogen

The intensity map and velocity field of the H_2 1-0 S(1) line emission in the central regions of PKS B1718–649 are shown in Figs. 5.4 left and right panels. At radii $r > 650$ pc, the H_2 is assembled in a disk aligned in the N-S direction, the same direction as the H I disk, H_α , and the dust lanes at larger radii ($r \sim 8$ kpc) (Keel & Windhorst 1991, Chapter 4). The H_2 disk reaches velocities of $\pm 200 \text{ km s}^{-1}$, which is similar to the rotational velocities of the large scale H I disk Chapter 4 From now on, we refer to it as the ‘outer disk’ of

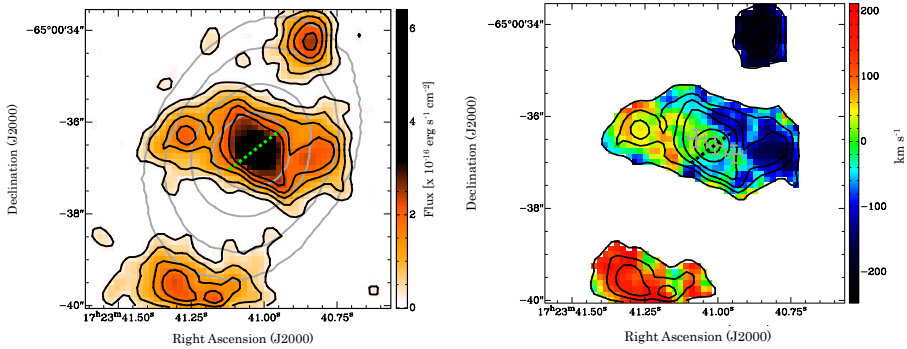


Fig. 5.4: *Left panel:* Intensity map of the H₂ 1-0 S(1) line in the inner 2 kpc of PKS B1718–649. The position angle of the radio source is shown in dashed green (PA= 135°). Intensity contours at 1.5, 3, 5, 7, 9, 12, and 15- σ are shown in black, starting from $1.5\sigma = 2.5 \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2}$. The isophotes in grey show the distribution of the stellar component. *Right panel:* Velocity field of the H₂ 1-0 S(1) line with the contours of the intensity map overlaid. The position angle of the radio source is shown in black. Velocities are given relative to the systemic value, $v_{\text{sys}} = 4274 \text{ km s}^{-1}$. The regions marked by crosses are those where we extracted the profiles of Fig. 5.5, (see the text for more details).

H₂. At radii $r < 650 \text{ pc}$, the major axis of the H₂ disk abruptly changes orientation from approximately north-south (PA $\sim 170^\circ$) to east-west (PA $\sim +85^\circ$). We therefore refer to this as the ‘inner disk’ of H₂. The outer disk has asymmetries extending towards the inner disk, possibly suggesting that inner and outer disks are a part of a single, strongly warped structure. From the stellar continuum, we determined the distribution of the stars in the field of view (see the grey isophotes in Fig. 5.4 (left panel)). The outer disk is aligned with the stellar component in the N-S direction. Conversely, the inner disk is polar.

In the inner disk, the major axis is aligned in the E-W direction perpendicular to the outer disk. As we move towards the centre, the velocity field suggests that the kinematic minor axis of the disk (green velocities in Fig. 5.4 (right panel)) may change its orientation within $1''$ from the radio source. There, its axis of rotation appears to be aligned with the direction of propagation of the radio jets (dashed line in the figures). However, given the quality of the data, the presence of this warp should only be considered as a suggestion.

5.3.2 The H₂ 1-0 S(1) line in the innermost 75 pc

The velocity field in Fig. 5.4 (left panel) suggests that, overall, the disk is dominated by rotation. However, as mentioned above, the very central region ($r < 0.25''$) shows a broader profile compared to the neighbouring regions, suggesting a much larger velocity dispersion in the innermost $\sim 75 \text{ pc}$. In Fig. 5.5, we show the H₂ 1-0 S(1) line profile extracted from the nucleus ($r \sim 0.25''$) and from two adjacent regions on either side of the nucleus (crosses in Fig. 5.4 (right panel)). The line extracted from the central region (C) is shown in Fig. 4, along with the H₂ 1-0 S(1) line from two regions adjacent to the centre

on the east (E) and on the west (W), respectively. All spectra are centred on the systemic velocity of the galaxy. From the figure it is clear that the H_2 line has an asymmetric profile in the centre, with a second component peaking at velocities $> +220 \text{ km s}^{-1}$. This component lies outside the range of velocities of the rotation, limited by the flanks of the blue and red lines. The centre of the galaxy ($r < 75 \text{ pc}$) is the only region of the galaxy where the H_2 1-0 S(1) line has this feature.

This can also be illustrated by the position-velocity diagram extracted along the major axis of the inner disk ($PA \sim 85^\circ$). Figure 5.6 shows that the kinematics are generally characterised by rotation, as suggested by the smooth gradient in velocity along the x-axis, which is symmetric with respect to the centre of the galaxy and with respect to its systemic velocity. Nevertheless, in the centre ($r < 75 \text{ pc}$), the profile appears to be broader and more asymmetric towards red-shifted velocities ($v > +200 \text{ km s}^{-1}$) than in the rest of the disk.

Some considerations of the rotation curve of the inner disk of PKS B1718–649 allow us to explore the kinematics in more detail. Willett et al. (2010) estimate that the mass of the SMBH is $\sim 4 \times 10^8 M_\odot$. Assuming that the velocity dispersion of the stars is $\sim 200 \text{ km s}^{-1}$, this means that the SMBH dominates the kinematics of the galaxy out to $r \sim 45 \text{ pc}$, while beyond that radius, the stellar mass distribution, which is described well by a de Vaucouleurs profile (Veron-Cetty et al., 1995), also contributes. Figure 5.6 shows a rotation curve based on such a model where we have assumed a total mass of PKS B1718–649 of $4 \times 10^{11} M_\odot$, an effective radius of 9.7 kpc (Veron-Cetty et al., 1995), and circular orbits of rotation, and then corrected for the inclination of the inner disk². Looking at the central 75 pc , part of the broad profile can be described by the effect of the SMBH on the gas rotation. However, at red-shifted velocities ($v \gtrsim +220 \text{ km s}^{-1}$), there is gas extending beyond the velocity range of the rotation curve expected for the mass model: $\Delta v_{\text{uns}} \sim +150 \text{ km s}^{-1}$. Although our model is fairly qualitative, it suggests gas with anomalous velocities (Δv_{uns}) exists very close to the SMBH which may be directly involved in its fuelling (see Section 5.4 for more details).

5.3.3 The temperature and mass of the H_2

The relative intensity of the H_2 emission lines can be used to infer the temperature and mass of the molecular gas. We estimate the temperature in five different regions within the field of view from the flux densities shown in Table 5.2. As shown in Fig. 5.2, we chose two regions in the outer disk (R_N and R_S), two in the inner disk (R_N and R_S) and one in the centre (R_C). Following Jaffe et al. (2001); Wilman et al. (2005); Oonk et al. (2010) (and references therein), assuming that the gas is in local thermal equilibrium, the logarithm of the ratio between the flux density of a H_2 line and the flux density of the H_2 1-0 S(1) line depends linearly on the excitation temperature ($T_{\text{ex}}^{\text{rot}}$) of the gas itself. The flux ratios of the H_2 1-0 lines suggest that the inner and outer disks have temperatures between 1100 K and 1600 K , while the temperature is lower $\sim 500 \text{ K}$ in the centre. In the R_N and R_C regions, we measure upper limits for the H_2 1-0 S(0,2) line flux densities that are inconsistent with the local thermal equilibrium (LTE) temperatures derived from the 1-0 S(3) over 1-0 S(1) ratio. Deeper observations are needed to further investigate these possible deviations from LTE.

²The ratio between the minor and major axes of the inner disk, assuming a finite thickness, indicates the disk is oriented approximately edge-on ($i \sim 90^\circ$).

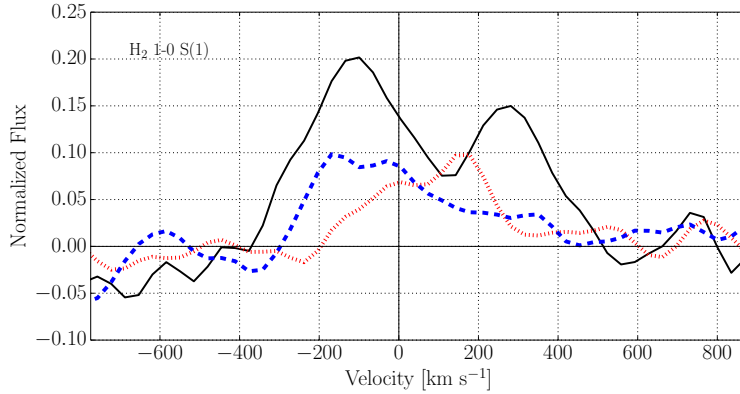


Fig. 5.5: Spectra of the H_2 1-0 S(1) line, centred at the systemic velocity of PKS B1718–649. Spectra are extracted along the line of sight to the radio source (black) and on a region on the east (red) and on the west (blue) of the inner disk, at $0.75''$ from the centre. Only the spectrum in front of the radio source appears broader and red-shifted.

The X-ray emission is localized in the innermost $2''$ of the galaxy. Considering that X-rays in the $[0.5 - 2]\text{keV}$ energy range could be strongly absorbed, we estimated the lower limit on the luminosity $L_{[0.5-2]\text{keV}} \gtrsim 10^{41} \text{erg s}^{-1}$ Chapter 4. This is only one order of magnitude higher than the H_2 luminosity of the inner disk, $L_{\text{H}_2} \sim 6.0 \times 10^{40} \text{erg s}^{-1}$ (where the flux density is $5.1 \times 10^{-14} \text{erg s}^{-1} \text{cm}^{-2}$ at $D_L \sim 62.4 \text{Mpc}$). This agrees with the thermal excitation scenario and suggests that only a small number of high-energy photons are required to produce molecular hydrogen emission. The small size of the radio source (2pc) hints that shocks, if present, may excite the warm molecular gas only in the regions right next to the radio jet ($r \ll 75 \text{pc}$). As a result, this cannot be the main excitation process of the H_2 , suggesting that thermal excitation is likely the main mechanism responsible for the warm H_2 emission.

Given the temperature of the molecular hydrogen, we determine the mass of the H_2 of the inner disk, $M_{\text{H}_2}(\text{warm}) \approx 1 \times 10^4 M_\odot$, from the flux density of the H_2 1-0 S(1) line, as shown in Turner et al. (1977), Scoville et al. (1982) and Dale et al. (2005). From the data cube, we also measure the flux density of the unsettled H_2 component in the innermost 75pc (see Section 5.3.2): $F \sim 6.5 \times 10^{-19} \text{erg s}^{-1} \text{cm}^{-2}$. This corresponds to $M_{\text{H}_2}(\text{warm}) \gtrsim 130 M_\odot$.

The amount of warm gas found in the inner disk of PKS B1718–649 is in the same range of masses as found in the innermost hundreds of parsecs of other LINER galaxies (Müller-Sánchez et al., 2013). Since the H_2 is mainly thermally excited, the H_2 1-0 S(1) line may reflect the total mass of the cold molecular component, i.e. the H_2 in its ground state ($T_{\text{exc}} \sim 100 \text{K}$) commonly traced by the CO lines and the H_2 0-0 S(0,...,7) rotational lines. Within one order of magnitude, the mass of the cold H_2 can be estimated from the mass of the warm H_2 . We find $M_{\text{H}_2}(\text{cold}) \approx 2 \times 10^9 M_\odot$ for the inner disk and $M_{\text{H}_2}(\text{cold}) \gtrsim 5 \times 10^7 M_\odot$ for the unsettled H_2 in the central 75pc , where we use the relation found for a sample of galaxies with similar morphological classification to PKS B1718–649, (Mueller Sánchez et al., 2006; Dale et al., 2005; Mazzalay et al., 2013; Emonts et al., 2014).

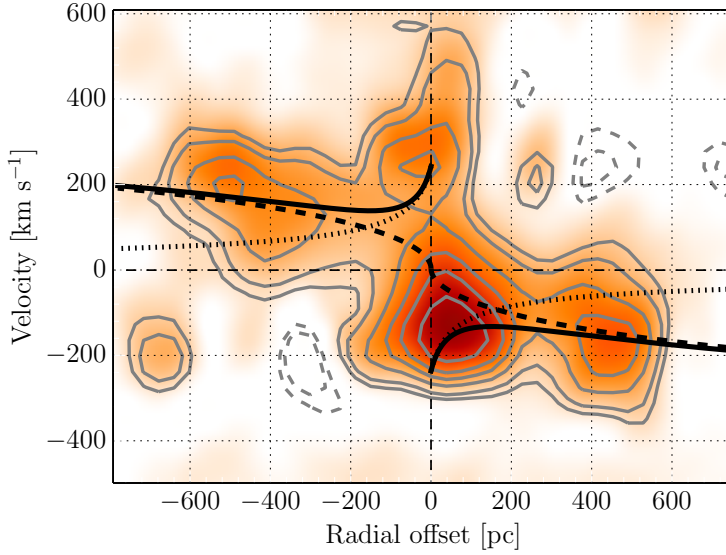


Fig. 5.6: Position velocity plot of the H_2 1-0 S(1) line extracted along the major axis of the inner disk. Contour levels are $-3, -2, 2, 3, 5, 7, 9$, and $12\text{-}\sigma$. The black dashed line shows the rotation curve predicted from the stellar photometry, while the fine dashed line shows the contribution of the SMBH to the rotation. The solid line is the total rotation curve derived from the two. In the centre at velocities $\gtrsim +220\text{ km s}^{-1}$, we identify a component of H_2 deviating from the predicted rotation curve (see Section 5.3.2 for further details).

5.4 Relating the kinematics of the gas to the radio nuclear activity

The SINFONI observations in the innermost kilo-parsec of PKS B1718–649 reveal two disks of molecular hydrogen. The outer disk ($r > 650\text{ pc}$), oriented in the N-S direction, follows the rotation of the stars and of the other gaseous components of the galaxy. The inner disk ($r \lesssim 600\text{ pc}$) is oriented E-W with kinematics characterised overall by rotation. In Section 5.3.2, we showed that in the innermost 75 pc of PKS B1718–649, the H_2 1-0 S(1) line is brightest and asymmetric, suggesting the presence of a second component of H_2 with unsettled kinematics deviating from the rotation with red-shifted velocities $\Delta v_{\text{uns}} \sim +150\text{ km s}^{-1}$.

The H_2 is not the only gaseous component with unsettled kinematics near the radio source. Along the same line of sight (and in particular only in front of the central 2 pc of the radio source), the H I also shows kinematics deviating from regular rotation Chapter 4. Two separate absorption lines with opposite velocities with respect to the systemic value suggest the presence of small clouds of cold gas close to the AGN that deviate from the rotation of the other components of the galaxy. From the separation between the two lines, we estimate that these clouds have unsettled velocities of $v_{\text{uns}}(\text{H I}) \sim 100\text{ km s}^{-1}$. Given that the distribution of the H_2 in the inner disk is not homogeneous, it is reasonable to assume that the H I clouds are located in the same

Table 5.3: Main properties of the molecular hydrogen in the innermost regions of PKS B1718–649.

Parameter	Inner disk	Deviating component
Radius [pc]	<650	< 75
Flux [$\text{erg s}^{-1} \text{cm}^{-2}$]	5.1×10^{-14}	1.5×10^{-15}
Luminosity [erg s^{-1}]	3.5×10^{40}	5.7×10^{38}
Temperature [K]	~ 1100	~ 900
Mass H_2 (warm) [M_\odot]	$\sim 1.5 \times 10^4$	$\gtrsim 130$
Mass H_2 (cold) [M_\odot]	$\sim 2 \times 10^9$	$\sim 5 \times 10^7$

region of the H_2 with unsettled kinematics, i.e. in the innermost 75 pc of the galaxy. The presence of a clumpy multiphase environment around the radio source is also suggested by the variability of its radio-continuum (Tingay et al., 2015), which has been attributed to changing conditions in the free-free absorption in a surrounding clumpy cold medium. Moreover, optical spectroscopic observations also suggest the presence of a clumpy circum-nuclear medium (Filippenko, 1985). A similar distribution of H_2 with increasing velocity dispersion in the central ~ 100 pc has been detected in a number of different AGN and Seyfert galaxies (Hicks et al., 2009, 2013; Davies et al., 2014; Guillard et al., 2012; Müller-Sánchez et al., 2013; Mazzalay et al., 2013; Mezcueta et al., 2015).

PKS B1718–649 is thus a newly born compact radio AGN surrounded by a rotating clumpy multi-phase circum-nuclear disk, where we measure deviations from rotation in the H I and the H_2 only in the innermost 75 pc. While the H I —because it is detected in absorption—must be located in front of the radio source, the H_2 is detected in emission and can be located either in front of or behind the radio source, or both at once. In principle, therefore, the red-shifted velocities of the unsettled gas could correspond to either an infall or an outflow. It is difficult to disentangle this from the available data. However, given the properties of this AGN, we note it is unlikely that it is driving an outflow. The small scale of the radio source (2 pc) and its low jet power ($P_j \lesssim 2.3 \times 10^{43} \text{ erg s}^{-1}$) would exclude a jet-driven outflow. Since PKS B1718–649 is a LINER galaxy, the radiation from the optical AGN is also limited ($P_{\text{rad}} \lesssim 8 \times 10^{43} \text{ erg s}^{-1}$), and an outflow is not likely to occur on energetic grounds. These considerations make it plausible to assume that the red-shifted, unsettled velocities of the H_2 are connected to gas falling into the AGN and perhaps being responsible for its fuelling. PKS B1718–649 does not show traces of previous periods of radio activity that could have perturbed the gas³. As a result, it is likely that, when the radio source was triggered, these clouds with unsettled kinematics ($\Delta v_{\text{uns}} \sim +150 \text{ km s}^{-1}$) were already present in the innermost 75 pc of the circum-nuclear disk. The double disk structure of the H_2 and the large-scale strongly warped H I disk suggest that the gas in PKS B1718–649 is still settling in the gravitational potential and that stellar torques are acting on the gas to align into a stable configuration. These torques may strip gas clouds from the inner two-disk configuration so that the clouds subsequently become unsettled and fall towards the SMBH.

Simulations of black hole accretion in rotating environments (King et al., 2008; Nayakshin & Zubovas, 2012; Gaspari et al., 2013; Gaspari, 2015) have suggested that, because of the local instabilities of the medium, chaotic collisions between clouds,

³Since the 1.4 GHz continuum flux density over $\sim 4 \text{ pc}^2$ (beam of the VLBI observations, Tingay et al. (2002)) is the same as over $\sim 64 \text{ kpc}^2$ (resolution of the ATCA observations, Chapter 4).

cold filaments, and the clumpy circum-nuclear disk may unsettle the kinematics of the gas and promote the cancellation of angular momentum. This may lead to the triggering of accretion into the SMBH. If the velocity dispersion does not exceed the rotational velocity, the accretion rates onto the AGN are predicted to be $\lesssim 0.1 M_{\odot} \text{ yr}^{-1}$. This scenario could be an alternative explanation for the disturbed kinematics observed in the H I and the H₂ of PKS B1718–649, where the deviations from rotation ($\Delta v_{\text{uns}} \sim +150 \text{ km s}^{-1}$) are in the same order of magnitude as the rotational velocity ($v_{\text{rot}} \sim 220 \text{ km s}^{-1}$). This scenario predicts inefficient accretion onto the AGN, which is also suggested by the radio power and by the LINER nature of PKS B1718–649.

In low-efficiency radio AGN, the radio power may set a constraint on the accretion rate onto the SMBH (Allen et al., 2006; Balmaverde et al., 2008). In PKS B1718–649, this is equal to $\dot{M} \lesssim 10^{-2} M_{\odot} \text{ yr}^{-1}$. In Chapter 4, we derived a limit for the contribution of the H I to the accretion using a very uncertain distance of the clouds from the nucleus owing to the large beam of the H I observations. The H₂ emission allows us to constrain this distance to $\lesssim 75 \text{ pc}$, so we determined the accretion rate of the H I clouds and of the H₂ with unsettled kinematics and investigated whether this could sustain the radio activity. Assuming the velocities deviating from rotation are equal to the in-fall velocity into the black hole ($v \sim +150 \text{ km s}^{-1}$) and assuming a distance of the clouds from the SMBH $r \lesssim 75 \text{ pc}$, we determined a typical timescale of accretion of these components to be $t_{\text{accretion}} \sim 6.9 \times 10^5 \text{ years}$. The mass of the H I clouds is constrained by the column density of the absorption lines; assuming these are located within $\sim 75 \text{ pc}$ of the radio source, we determined $M_{\text{HI}} \sim 3.5 \times 10^2 M_{\odot}$. From this, it follows that $\dot{M}_{\text{HI}} \sim 10^{-4} M_{\odot} \text{ yr}^{-1}$, which is insufficient, alone, to sustain the radio activity. In the innermost 75 pc, the warm molecular hydrogen with unsettled kinematics has a mass of $M_{\text{H}_2}(\text{warm}) \lesssim 130 M_{\odot}$, which also gives an accretion rate of $\dot{M}_{\text{H}_2} \sim 10^{-4} M_{\odot} \text{ yr}^{-1}$. If some of the cold H₂ ($T_{\text{ex}} \sim 10^2 \text{ K}$, see Section 5.3.3) is also involved in feeding the AGN, we may obtain an accretion rate sufficient to power such a radio source.

PKS B1718–649 has some interesting features in common with the nearest radio galaxy Centaurus A. Like PKS B1718–649, Centaurus A has a young radio core surrounded by a circum-nuclear rotating disk of H₂ that is embedded in a large-scale H I disk (Struve & Conway, 2010). Centaurus A also shows a brighter and asymmetric H₂ line profile in the innermost 200 pc. This can be explained by gas streaming down into the AGN (Neumayer et al., 2007). PKS B1718–649 appears to be another example where we witness the fuelling of a radio-loud AGN. We plan to investigate this further with future observations.

5.5 Conclusions

Our SINFONI $[1.95 - 2.45] \mu\text{m}$ observations of the innermost $8'' \times 8''$ of PKS B1718–649 have shown the presence of molecular hydrogen assembled into two orthogonal disks. The outer ($r > 650 \text{ pc}$) disk of H₂ is oriented in the north-south direction aligned with the stellar distribution and of which the kinematics connects smoothly to that of the large-scale H I disk. At radii $r < 650 \text{ pc}$, the H₂ was assembled in an inner circum-nuclear disk, aligned in the east-west direction and polar with respect to the stars. The kinematics of the disks is characterised by rotation with velocities of about 220 km s^{-1} . Assuming thermal equilibrium within the disk, we determined the temperature of the H₂ to be $T_{\text{ex}} \sim 1100 \text{ K}$ and its mass $M_{\text{H}_2}(\text{warm}) \approx 1 \times 10^4 M_{\odot}$, which may trace up to $\sim 2 \times 10^9 M_{\odot}$ of cold molecular hydrogen.

The kinematics of the inner disk of H_2 is characterised by rotation due to the combination of the stellar distribution and the SMBH (see Section 5.3.2). Close to the radio source, at radii $r < 75$ pc, we detected H_2 deviating from such a rotation. In the innermost 75 pc, the H_2 has unsettled kinematics in the range $\Delta v_{\text{uns}} \sim +150 \text{ km s}^{-1}$. This component of warm H_2 has a mass of $\sim 130 M_{\odot}$, which may trace $\lesssim 5 \times 10^7 M_{\odot}$ of cold molecular hydrogen. The H I clouds detected in absorption against the compact radio core by Chapter 4 have similar velocities deviating from rotation, and they could be located in the same region close to the radio source. These observations, along with the information collected from the variability of the radio continuum (Tingay et al., 2015) and the line ratios of the optical forbidden lines (Filippenko, 1985), suggest that the circum-nuclear ISM is clumpy and may represent the fuel reservoir of the radio source. The mass traced by the H I clouds and by the warm H_2 alone is insufficient to fuel the AGN to power the radio jets. Instead, the mass of total cold H_2 ($T_{\text{ex}} \sim 10^2 \text{ K}$) traced by the warm unsettled H_2 in the innermost 75 pc could fuel the radio source at the required accretion rate. Given the low power of the AGN, inefficient accretion is most likely to occur in PKS B1718–649. Given the double disk structure of the H_2 , which is part of the larger ($r \sim 23$ kpc) H I disk, the gas configuration could be caused by the stellar torques acting on the gas to align into a stable configuration, and it may give rise to small clouds with unsettled kinematics. The small clouds of H I and H_2 with unsettled velocities of $\sim 150 \text{ km s}^{-1}$, which we detect, could be falling into the AGN, contributing to the fuelling of the radio source.

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